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SPECIAL TECHNICAL REPORT #1

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THE EFFECT OF 3.39 MICRON SUPERRADIANCE ON THE 0.6328 MICRON OUTPUT POWER OF A HELIUM-NEON LASER

J. S. Hancock and J. A. Carruthers

Contract No. DA-31-124 ARO-D-402
Advanced Research Projects Agency
Project DEFENDER
ARPA Order No. 675

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF MINNESOTA
MINNEAPOLIS, MINNESOTA

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The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

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FOREWORD

The research described in this Special Technical Report was carried out in the Department of Electrical Engineering, University of Minnesota, under Contract DA-31-124 ARO-D-402, Advanced Research Projects Agency, Project DEFENDER, ARPA Order No. 675.

The research is aimed at improving high power helium-neon lasers for use in nonlinear optics. The technical work was carried out by John S. Hancock in partial fulfillment of the requirements for the degree of Master of Science.

This report was submitted by the authors August 1967.

ABSTRACT

The effect of competition in a 0.6328 micron helium-neon laser from the high-gain 3.39 micron line has been studied. The 50 milliwatt laser used for the investigation employs a six-foot Brewster-angle tube and has a prism at one end to insure that oscillation occurs only at 0.6328 microns. The double-pass gain of the tube at 3.39 microns is of the order of 10^5, and the investigation was designed to determine whether the resulting infrared superradiance is detrimental to the operation of the visible laser. Measurements were made of the 3.39 micron superradiance from one end of the tube when various calibrated reflectors were placed at the other end. With a typical dielectric coated mirror, designed for maximum reflectivity at 0.6328 microns, the superradiant 3.39 micron power from the other end of the tube was 75 microwatts. This result shows that in a 6 foot visible laser filled with a 10:1, He^3-Ne mixture and employing a single prism for frequency selection, the 3.39 micron superradiance does not significantly affect the visible output power. However, the superradiance is about 2 orders of magnitude larger than estimated from theory, and presumably results mainly from multiple reflections from the tube walls.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. SYNOPSIS

Of the many lasers discovered since the original work of Maiman,[1] Collins, et al.[2] and Javan, Bennett and Herriott,[3] the 0.6328 micron helium-neon laser[4] has become one of those most widely used. As well as having the advantage of being in the visible region of the spectrum, it is dependable, long-lived, and comparatively inexpensive. Although the power output of most general purpose 0.6328 micron lasers is in the 0.25 - 2.5 milliwatt range, research in holography and nonlinear optics has forced the development of high power versions capable of 50 - 200 milliwatts.

These special high-power visible lasers are usually about two meters long, and a problem arises from competition between the 0.6328 micron and the 3.39 micron transitions. The competition results from the fact that the two transitions originate from the same upper energy level, and thus they compete for the same excited atoms. The transitions are described in Paschen notation as $3s_2 - 2p_4$ and $3s_2 - 3p_4$ for the 0.6328 micron and the 3.39 micron neon lines respectively. When the effect becomes significant, as is the case for discharge lengths of about one meter, the higher gain transition tends to dominate the other, and with the onset of oscillation the upper state population is reduced so that laser action on the lower gain transition becomes difficult.[5] Gain figures of 20 to 50 dB per meter at 3.39 microns are reported in the literature[6,7,8,9] and it is apparent that under many circumstances this transition may severely limit the output of the 0.6328 micron line, where the gain is only about 5 percent per meter.

Although lasing action has been observed for several neon transitions in the red and infrared spectral regions, this study is concerned only with the 0.6328 micron and 3.39 micron lines. For convenience these will often be referred to as the visible and infrared transitions, respectively.

The effect of the 3.39 micron transition on the visible laser was pointed out by Bloom, Bell and Rempel who first observed laser oscillations at 3.39 microns in a helium-neon mixture.[10] It was discovered that lasers could be made to oscillate simultaneously on the visible and 3.39 micron lines, and when this occurred the power output in the visible was significantly reduced.

All 0.6328 micron lasers make use of some technique to suppress the infrared transition. For tubes of about 50 cm and less the frequency selectivity inherent in dielectric coated mirrors is sufficient to insure that competition effects can be neglected. Hence the 3.39 micron line does not present a problem for the small general-purpose lasers used for alignment, etc. But high-power 0.6328 lasers are usually one to four meters long, and positive means must be provided for suppressing the infrared transition.

In addition to the use of dielectric coated mirrors there are several methods available for helping decrease competition from the infrared line. These include insertion into the cavity of an infrared absorbing vapor such as toulene, application of a dc magnetic field, and the use of a prism for tuning the laser cavity to the 0.6328 micron line. A high quality prism was available for the laser used in this investigation and details of the system are discussed in the next paragraph and in section II-A. The effect of a dc magnetic field on the performance of a visible laser is extremely complex and this aspect was examined only in a very preliminary manner. A non-uniform magnetic field of about 100 gauss was found to suppress oscillation at 3.39 microns, and probably its effect is associated with broadening of the 3.39 micron line through Zeeman splitting of the levels. The visible transition is also broadened, but the infrared line is more sensitive to the magnetic field since it is initially much narrower. The magnetic field also alters the motion of the plasma electrons, and for this reason can change the visible output power. Because of the difficulty in separating the electron cyclotron effects from those due to suppression of the 3.39 micron line, a magnetic field has not been used during this work except in the course of preliminary checks on the maximum output power of the 0.6328 micron laser.

By placing a prism in the laser resonator it is possible to tune the cavity to the desired transition. Because of optical dispersion the angle of deviation is a function of wavelength, and for the fused quartz prism used in this experiment there is approximately 5° difference in the deviation for the 0.6328 and 3.39 micron lines. This means that when the mirrors are aligned for the visible transition the mirror at the prism end of the laser is approximately 5° misaligned for 3.39 microns. This prism is cut and positioned so that the 0.6328 micron radiation enters and leaves at the Brewster angle. When made from high quality fused quartz and expertly polished the prism introduces negligible loss at 0.6328 microns.

Although the introduction of a prism into the laser cavity has proved successful in preventing oscillation at 3.39 microns,[5] serious competition effects remain in long tubes. Spontaneous emission that has been amplified during a double pass down the length of the tube becomes significant for long discharge lengths. The double pass results from the fact that the 3.39 micron radiation is reflected back down the tube by the mirror at one end, even though the prism at the other end breaks the feedback loop. The gain of the 3.39 micron line is large enough so that for long tubes the amplified spontaneous emission produces significant depletion of the population in the upper level even when dielectric coated mirrors are employed. The next logical step in decreasing superradiance is to put a prism at both ends of the laser. Nevertheless, if the tube is lengthened sufficiently, the point is reached when amplification during a single pass will deplete the population of the upper level.

A paper by White and Rigden[8] on 3.39 micron superradiance discusses the competition problem for a 2 meter tube of 3 mm bore, for which a gain of 40 dB per meter is reported. Details of gas mixture and pressure are not given, but by reference to other published data from the same authors and others,[6,7,9] it can be inferred that the gas fill is about 0.5 Torr and a 5:1 He-Ne mixture. Present practice in this laboratory for 0.6328 micron lasers is to use a 10:1 mixture of He^3-Ne at a pressure of 2 to 3 Torr. The gain at 3.39 microns under these conditions should be significantly less than that reported by White and Rigden, and hence their results are not directly applicable.

The effect of superradiance can be estimated from theory, by integrating the amplified spontaneous emission over the entire volume of the tube. But such calculations are only very approximate because it is necessary to consider low-angle scattering from the walls of the laser tube. Consequently the only means of determining whether significant competition is present in a particular configuration is to measure directly the 3.39 micron superradiant power.

A six-foot tube of 4 mm bore was chosen for this study. The superradiant 3.39 micron power from one end of the tube was measured when various mirrors were in place at the other end. When a high-reflectivity 0.6328 micron dielectric coated mirror was used the 3.39 micron power was 75 microwatts. Since the ratio of photon energies is approximately 5, this result implies that the depletion of the upper level would rob the 0.6328 laser of 0.4 milliwatts, a small value when compared with the maximum power of 50 milliwatts. However, the superradiance was about 2 orders of magnitude higher than the calculated value, indicating that most of the 3.39 micron radiation results from amplified spontaneous emission undergoing multiple reflections from the walls of the tube.

These results correspond to operation in the absence of oscillations at 0.6328 microns. Consequently, the approach over-estimates the effect of superradiance on an operating visible laser. It is therefore recommended that measurements be made of the superradiance while the laser is operating in order to determine how much the 3.39 micron gain is reduced by the laser-induced transitions at 0.6328 microns. If the exponential gain coefficient at 3.39 microns were reduced by a factor of two, as is quite possible when the system is lasing at 0.6328 microns, then a 12 foot laser with a prism could be operated without significant power loss from the infrared superradiance.

II. TECHNICAL DISCUSSION

A. The High Power Visible Helium-Neon Laser

1. General background

The first continuously operating helium-neon laser was constructed by Javan, Bennett and Herriott[3] in the fall of 1960 and operated at 1.15 microns. It consisted of a Fabry-Perot interferometer with plane mirrors connected by bellows to a one meter discharge tube containing the active gas. Amplification was achieved by the induced emission of excited atoms in the upper state of the laser transition, and the process was such as to preserve the frequency, phase, and directionality of the beam. In subsequent lasers the plane mirrors were discarded in favor of spherical mirrors for which adjustment errors of several seconds of arc can be tolerated. In place of the internal reflectors and bellows of the original laser most modern systems use external reflectors with the ends of the tube terminated by windows oriented at the Brewster angle to eliminate unwanted reflections.

The interferometer constitutes a multimode resonant cavity, and if the gain of the amplifying medium is greater than the cavity losses, light emitted spontaneously into the modes is amplified and the power increases until saturation occurs and equilibrium is established. Fabry-Perot interferometers have been analyzed in detail by Fox and Li,[11] Boyd and Gordon,[12] and Boyd and Kogelnik.[13] Because transition linewidths in the optical and infrared regions of the spectrum are broad compared to cavity resonances, the laser frequency characteristics are determined to first order by the cavity properties.

The random motions of molecules in the gas cause the laser transition to be Doppler broadened. The linewidth determined by the radiative lifetime τ is equal to $1/2\pi\tau$, and for the 0.6328 laser this width is about 30 MHz. Since the molecules are all traveling with different velocities due to thermal motion, the resultant linewidth is broadened by an amount approximately equal to the Doppler shift associated with the mean molecular velocity. Doppler broadening is a form of inhomogeneous broadening since only the atoms with a particular velocity will interact with a light wave of a particular frequency. Consequently, when the laser oscillates in several modes, holes are burnt into the Doppler curve because of depletion of the population of molecules whose Doppler-shifted transition frequencies correspond to the mode frequencies. For the 0.6328 micron line the Doppler width is about 1500 MHz.

The frequency separation for the lowest order interferometer modes is approximately c/2L where c is the velocity of light and L is the laser length. For the laser used in these experiments the intermode spacing is about 75 MHz and therefore about 15 axial modes are present in the output. In addition higher order, off axial modes may occur.

Operation in only the lowest order modes can be insured by proper selection of mirror radii. Experience in this laboratory indicates that the off axial modes are suppressed if the mirrors and tube bore are chosen so that the bore radius is twice the radius of the lowest order mode at the point where the mode is largest. Diffraction loss for the axial mode is then negligible.

The reflectivity of one mirror is chosen to provide maximum output power. The mirror transmission should be between 1% and 5% for high power visible lasers, depending on the length of the tube, but mirror quality is also of major significance.

White and Gordon[14] have reported on optimum gas mixture and pressure for a helium-neon visible laser. These authors found that for maximum gain a 5 to 1 ratio of He to Ne should be used at a pressure given approximately by p = 3/d Torr, where d is the bore in millimeters. However, experience in this laboratory has indicated that in order to obtain a large increase in tube lifetime, at a very small sacrifice in power, it is advisable to use a 10 to 1 mixture at a pressure 2 to 3 times higher.

DC excitation has been used throughout except for checks made to determine how large a power increase could be obtained by using rf excitation. Since only about a 0.5 dB increase in output resulted, rf excitation was discontinued.

2. Laser design details

A tube bore of 4 mm was selected so that axial mode output could be achieved using commercially available mirrors. The mirrors chosen consisted of a flat and a curved mirror at 6.8 meter radius. The resulting mode diameters at the curved and plane mirrors are about 2 mm and 1.5 mm respectively. These mode diameters can be calculated from[15]

$$w_1^4 = \left(\frac{\lambda}{\pi}\right)^2 \frac{b_1^2 L}{b_1 - L}$$

and

$$w_2^4 = \left(\frac{\lambda}{\pi}\right)^2 L(b_1 - L)$$

where w_1 and w_2 are the spot sizes (radius) at the curved and plane mirrors respectively, b_1 is the radius of curvature of the spherical mirror and L is the length of the cavity. The mirror transmission required for optimum output coupling was determined by experimenting with various reflectivities. It was found that the output power depended only slightly on mirror transmission ranging from 2% to 4%. The reflectivities used were 99.6% for the plane mirror and 2.6% transmission for the curved mirror.

The tube was filled with a 10 to 1 mixture of He^3-Ne at a pressure of 3.1 Torr. This pressure was higher than optimum pressure, but was used to allow operation at lower discharge currents in order to increase the lifetime of the tube. Optimum pressure was found to be about 2.0 Torr with the power peaked at 23 milliamps. At 3.1 Torr the power peaked at about 12 milliamps and was 0.5 dB down from the value obtained at 23 milliamps and 2.0 Torr.

A flat optical bench, on which mirror mounts, prism, and laser tube were fastened, was made by attaching a 1' x 8' slab of 1/2" aluminum tooling plate to a 6' length of 8" heavy webb aluminum channel base (Figs. 1 and 2). Adjustment of the mirrors was accomplished by means of three 1/4 - 56 bolts which acted to compress rubber washers.

The fused quartz prism used to eliminate simultaneous oscillations at 3.39 microns was positioned at the high reflectivity end and oriented as shown in Figs. 3 and 4. The distance between the prism and the mirror was made as large as the dimensions of the optical bench would allow, thereby increasing the losses at 3.39 microns. Both the quartz window at the end of the tube and the prism were inclined at the Brewster angle so as to minimize reflection losses. The Brewster angle surfaces will completely transmit only radiation with the electric field in the plane of incidence, hence this discriminatory action causes the laser light to be polarized.

B. Estimation of Superradiant Power

Superradiance results from the amplification of its own spontaneous emission by a medium in which there is population inversion. The magnitude of the superradiance for a particular tube geometry can be estimated from theory. An expression has been obtained by Birnbaum,[16] who adopted approximate equations for the power from a single-mode laser to the special case where one mirror is removed from the system. However, a more direct derivation is followed here in order to illustrate the principles involved. Approximations are present in both methods of approach, but the values obtained are equal within a factor of about 3, which is well within the accuracy that can be expected.

Figure 5 illustrates the geometry for the calculations. A straight tube of length L and radius a is assumed to be filled with the active material. This corresponds to the condition when no mirror is present, but the calculation is easily extended to include a mirror of finite reflectivity at one end. Saturation is neglected and a uniform population inversion is presumed throughout. The possibility of significant saturation is examined in section II-C and found to be small.

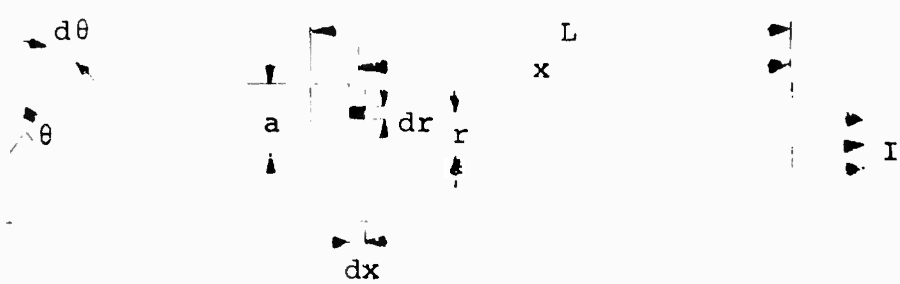

Figure 5 Geometry for calculation of superradiance

Because of the very high gain which is present, it is possible to make some simplifying approximations which ease the calculation of superradiance. First, the power out one end arises mainly from the flourescence near the other end, with amplification occurring over nearly the full length of the tube. Therefore only the spontaneous emission within the solid angle subtended by the tube aperture at a distance equal to the length of the system needs to be considered. Second, line-narrowing effects occur, and because of the high gain, the spectral width of the superradiance is small compared with the Doppler-broadened linewidth. Further this width is different only by a factor of $\sqrt{2}$, whether the system consists of the simple tube of length L, or consists of the tube with a totally reflecting mirror at one end and an effective length of 2L. Therefore the spectral width will be estimated and assumed to be constant for any of the conditions used in the experiments.

Before an estimate of the superradiant power can be made the value of the exponential gain coefficient at 3.39 microns is required. All of the published data are for larger diameter tubes and lower pressures than used in these experiments. The most comprehensive data available is that reported by Moeller and McCubbin[9] for a tube bore of 7 mm. From their curves an estimate of the gain can be obtained for the 4 mm tube at 3.1 Torr. It is assumed that the maximum gain obtained in a tube, when the current is adjusted, depends only on the product of tube diameter and pressure (for a particular He-Ne mixture). Therefore, the gain for the 4 mm tube at 3.1 Torr should be the same as that for a 7 mm tube at 1.8 Torr. According to the graphs this value is 19 for a tube 107 cm in length and for a 10:1 mixture of He-Ne. This corresponds to an exponential gain coefficient of 0.035 cm^{-1} when allowance is made for the use of He^3 in the tube instead of the lower gain He^4. The 0.035 cm^{-1} gain coefficient means that the single-pass gain is about 400 for the 170 cm active tube length.

Returning to the calculation, the number of photons emitted spontaneously per second from a differential volume of gas is

$$\dot{N} = \frac{n_i}{\tau} r\, dr\, d\theta\, dx \qquad (1)$$

where n_i is the population density of the upper (ith) level, and τ is the radiative lifetime associated with radiation emitted spontaneously by the ith level to the lower (jth) level of the laser transition. Of these only the fraction contained in the solid angle subtended by the end of the tube are properly directed to pass out the far end. The solid angle is very nearly independent of r and the fraction is approximately given by $\pi a^2/4\pi x^2$ or simply $(a/2x)^2$.

In passing down the length of the tube the photons experience $e^{\alpha(\nu)x}$ gain where $\alpha(\nu)$ is a function of frequency and for a Doppler broadened line is given by

$$\alpha(\nu) = \alpha_o\, e^{-(\ln 2)(\nu-\nu_o)^2/\Delta\nu_D^{\,2}} \tag{2}$$

The center frequency is ν_o and $\Delta\nu_D$ is the Doppler half width at half maximum. However in the calculation of the total superradiance, instead of integrating over all frequencies, the half power width of the amplified flourescence is estimated and α is treated as a constant α_o.

To obtain an estimate of the half power width, designated $\Delta\nu_s$, Eq. (2) is expanded in Taylor series and only the first two terms retained.

$$\alpha(\nu) \simeq \alpha_o\left[1 - (\ln 2)(\nu-\nu_o)^2/\Delta\nu_D^{\,2}\right] \tag{3}$$

At the half power point $\alpha(\nu) \simeq \alpha_o - \ln 2/L$. Therefore,

$$\alpha_o - \ln 2/L \simeq \alpha_o\left[1 - (\ln 2)\left(\frac{\Delta\nu_s}{\Delta\nu_D}\right)^2\right]$$

or

$$\Delta\nu_s \simeq \Delta\nu_D/(\alpha_o L)^{1/2} \tag{4}$$

Taking α_o as 0.035 cm^{-1} and L as 170 cm, then $\Delta\nu_s \simeq \Delta\nu_D/2.5$.

The contribution to the intensity out the end of the tube from the differential volume of gas is

$$dI = \frac{\dot{N}\, h\nu}{\pi\, a^2}\, e^{\alpha_o x} \left(\frac{a}{2x}\right)^2$$

or from Eq. (1)

$$dI = \frac{n_i}{\tau} \frac{h\nu}{\pi\, a^2}\, e^{\alpha_o x} \left(\frac{a}{2x}\right)^2 r\, dr\, d\theta\, dx \qquad (5)$$

Replacing x by L in the solid angle term and integrating Eq. (5) the following expression for I is obtained.

$$I = \frac{n_i}{\tau\alpha_o} h\nu \left(\frac{a}{2L}\right)^2 \left(e^{\alpha_o L} - 1\right)$$

or since $e^{\alpha_o L} >> 1$

$$I = \frac{n_i}{\tau\alpha_o} h\nu \left(\frac{a}{2L}\right)^2 e^{\alpha_o L} \qquad (6)$$

But α_o is related to the population inversion density n_i for a Doppler broadened line by[15]

$$\alpha_o = \sqrt{\frac{\ln 2}{\pi}}\, \frac{n_i \lambda^2}{8\pi\tau\Delta\nu_D} \qquad (7)$$

where it has been assumed, in the absence of saturation, that the lower level of the laser transition is essentially empty. Also the multiplicity of the levels has been neglected. Since the Doppler line is inhomogeneously broadened the above equation for n_i must be adjusted to compensate for the result of Eq. (4). That is, only about 1/2.5 of the total inverted population will contribute to the superradiance. With this in mind, by combining Eqs. (6) and (7),

$$I = \frac{8\pi h\nu}{\lambda^2} \left(\frac{a}{2L}\right)^2 e^{\alpha_o L} \left(\frac{\ln 2}{\pi}\right)^{-1/2} \frac{\Delta\nu_D}{2.5} \tag{8}$$

This yields a value for superradiant power P equal to I times πa^2, on the order of a 0.02 microwatts for a single pass. With a 100% reflectivity mirror at one end of the tube, corresponding to a double pass or a discharge length of 12 feet, the value obtained is about 2 microwatts.

The superradiant power out one end of the tube can be related to the reflectivity R of a mirror at the other end by

$$P = P_o + \frac{P_o}{4} RG \tag{9}$$

where P_o is the output superradiance for 0% reflectivity and G is the single-pass gain factor. The factor of 1/4 comes from the fact that placing the mirror at one end of the tube is equivalent to doubling the length of the tube thereby decreasing the solid angle by a factor of 1/4. For high values of reflectivity, a log-log plot of P versus R will be linear since $P_o << P_o$ RG/4. However, for low reflectivities where P_o exceeds P_o RG/4 some curvature is expected.

Equation (8) takes into account only the radiation passing down the tube within the solid angle determined by the length of the tube and bore. Neglected are the low angle reflections from the walls of the tube. Since Pyrex will reflect light incident at low angles, some of the spontaneously emitted radiation outside of the solid angle will be reflected from the walls and thus experience gain. This radiation will be diverging mo. rapidly upon leaving the tube than that passing within the solid angle subtended by the tube bore. For this reason, since it is the total superradiant power that is of interest in this investigation, the thermopile, which was used to measure superradiance, was placed as close to the end of the tube as the apparatus would allow.

C. Saturation Effects at the End of the Discharge Tube

To estimate the approximate amount of saturation produced by the amplified spontaneous emission at the output end of the system, the measured value of superradiance is used to calculate the induced emission.

The differential equation for the population inversion is

$$\frac{dn_i}{dt} = -A_{ij}n_i + B_{ij}\frac{I}{v}(n_i - n_j) + W_p$$

where I is the intensity of the radiation, W_p is the pump term and v is the propagation rate in the gas. A_{ij} is the Einstein coefficient associated with spontaneous emission and[15]

$$B_{ij} = \sqrt{\frac{\ln 2}{\pi}}\ \frac{\lambda^3 A_{ij}}{8\pi h \Delta\nu_D}$$

is the Einstein coefficient at the center of the Doppler broadened line corresponding to induced emission. When the intensity is small the equilibrium value of the population inversion is determined only by the spontaneous emission and the pumping rate. However, it is when the induced term becomes comparable to the spontaneous term that depletion or saturation effects occur. Consequently the ratio

$$\frac{B_{ij}\ I}{A_{ij}\ c} = \sqrt{\frac{\ln 2}{\pi}}\ \frac{\lambda^2\ I}{8\pi h\nu\Delta\nu_D}$$

where c is the speed of light, is a measure of saturation.

Using the value of intensity measured with the 100% reflector at one end of the tube, this ratio is of the order of one tenth indicating that under these conditions, saturation has only begun to occur at the end of the tube. The effect would be less were a 0.6328 micron dielectric coated mirror used.

D. Measuring Devices

The usual devices for measuring laser power at 0.6328 and 1.15 microns are not suitable for use at 3.39 microns and special instrumentation had to be provided. For power measurements at 0.6328 microns an EG and G lite mike was employed. However, the silicon cell in the lite mike cuts off at about 1.2 microns. Also the type S_1 photosurface of the 922 RCA phototube, used for relative measurements at 0.6328 microns, is not effective beyond this same wavelength. The type P Kodak lead sulfide ektron detectors have appreciable sensitivity at 3.39 microns and in some circumstances can be used in conjunction with a 3.39 micron narrow band filter if the 3.39 micron power is large enough. Nevertheless, blackened thermal detectors were employed for most measurements at 3.39 microns. The sensitivity of these detectors is constant from the visible to 3.39 microns and therefore can be calibrated at 0.6328 microns. Also, by having the sensitivity at 3.39 microns as high as in the visible and near infrared, it was much easier to discriminate by means of a filter against unwanted background radiation from the discharge tube than when using a lead sulfide detector.

1. Thermal detectors

A Narda microwave bolometer type N821B/38B1, was converted to an optical detector by exposing the filament and evaporating a thin film of lampblack on the exposed portion. The bolometer was mounted in an aluminum block as shown in Fig. 5 and used to measure the reflectivities of several aluminum coated quartz flats and a 0.6328 micron dielectric flat. The biasing and impedance matching circuit for the bolometer is shown in Fig. 6.

An Eppley thermopile No. 7948 was used to measure the superradiant power out the end of the tube for the different reflectors at the other end. The 3/8" diameter circular detection surface of the thermopile consisted of eight bismuth-silver elements coated with lampblack. The basic sensitivity of the thermopile without a window at a power level of 10 milliwatts is 0.127 mv/mw cm^{-2}. This low intensity calibration, against a reference thermopile, was supplied by the Eppley laboratory.

2. Narrow band filter

In order to eliminate extraneous radiation, a Spectrum-Systems dielectric coated bandpass interference filter was placed at the output end of the tube. The filter was 0.15 microns wide at the 5% points, 0.10 microns wide at the half power points, and 69% transmission at the 3.37 micron center frequency. A Kodak filter 1.0 microns wide at the 5% points was also used. But because of the larger bandwidth, the data obtained was discarded in favor of that obtained with the narrower Spectrum-Systems filter.

3. Readout devices

A Fluke model 841A electronic galvanometer with a sensitivity ranging from 2 nanoamps to 200 nanoamps per scale division and an impedance of 180 ohms, was used in conjunction with the thermopile.

For all measurements taken with the bolometer and the lead sulfide detector, a Hewlett Packard standing wave indicator was used as a meter amplifier. A United Transformer Co. No. A-11 impedance matching transformer was used to match the bolometer to the meter amplifier. The bandpass characteristics of the standing wave meter required the use of a 1000 Hz chopper to modulate the signal being observed.

E. Experimental Procedure

The reflectivities of the aluminum coated flats and the dielectric coated flat were determined with the bolometer by measuring the relative power of the incident and reflected beams from a 3.39 micron laser. Large wedge angle flats were employed to eliminate interference from the uncoated surface of the mirror.

For each measurement of superradiant power the mirror at one end was aligned by maximizing the amplified spontaneous emission out the other end. The lead sulfide cell, because of its large surface area and relatively fast response (as compared with the thermopile), was used for this purpose.

Special care had to be exercised with the bandpass filter since the reflectivity of the filter coupled with the mirrors was sufficient to allow oscillations at 3.39 microns. The quartz window on the thermopile also produced the same effect. The problem was resolved by tilting both the filter and the thermopile off axis until oscillations ceased. However, it was sometimes necessary to insert a 7.5 dB Pyrex glass attenuator, set at the Brewster angle, between the end of the tube and the filter so that the angle through which the filter was rotated was not enough to produce a significant change in transmission. Variation of filter transmission with angle was observed separately with a 3.39 micron laser and found to be negligible for angles less than about 5 degrees. The experimental setup for measuring superradiance is shown in Fig. 7.

III. RESULTS

The values of superradiant power, measured at one end of the six foot He-Ne laser tube for various reflectivity mirrors at the opposite end, are given in Table 1. With the 0.6328 micron dilective coated flat, the power measured was 75 microwatts. For all measurements the discharge current was 10 milliamps. Figure 8 is a plot of the data in Table 1.

Table 1

Reflectivity (%)	Superradiant Power (microwatts)
96	330
69	260
21	90
8	20
0	2
18 (0.6328 laser flat)	75

IV. DISCUSSION

The results indicate that for the laser used in these experiments, if operated with a single prism, there is no appreciable depletion of the upper level and consequently insignificant loss of power at 0.6328 microns due to the presence of 3.39 microns superradiance. On the one hand the gain at 3.39 microns is low because of the 10:1 mixture and the high pressure. On the other hand the measured output superradiance is about two orders of magnitude higher than that predicted theoretically and apparently arises from multiple reflections from the walls of the tube.

The 75 microwatt superradiant power, measured with the 0.6328 micron dielectric coated mirror, implies that the power lost in the visible is 300 microwatts. This figure, obtained by multiplying by the ratio of photon energies, is small compared with the 50 milliwatt output at 0.6328 microns.

The literature shows for tubes of a few millimeters in diameter the gain coefficient can vary from 0.035 cm^{-1} up to 0.1 cm^{-1} depending on the pressure and mixture. For the tube used here the lower value, corresponding to a double pass gain of about 400, applies. A 10:1 mixture at an increased pressure was used to extend the lifetime of the laser. In a paper by White and Rigdon[8] similar measurements of the effect of 3.39 micron superradiance on visible output power were made. However, considerably larger gains were reported for the small bore (3 mm) tubing and reduced pressures.

The superradiant power measured with the 90% reflectivity mirror (300 microwatts) is about 150 times that calculated (2 microwatts) from Eq. (8) using 0.035 cm^{-1} as the gain coefficient. In order to make the calculated value comparable to the measured value, the gain coefficient would have to be increased to 0.050 cm^{-1} corresponding to a double pass gain of 75 dB. The Moeller and McCubbin[9] data shows that such a value is not attainable even at optimum pressure. The difference between calculated and measured values implies that the output superradiance arises mainly from multiple reflections. This follows because in the calculation only radiation passing within the solid angle determined by the tube aperture is considered. The magnitude of the difference indicates that the field of view of the system is approximately 10 times the angle subtended by the end of the tube. Since the multiple reflections control the amount of output superradiance, calculations should be made which take this into account. But, the accuracy of such a calculation would be limited because of the roughness of the drawn glass tube.

The plot of superradiant power versus mirror reflectivity (Fig. 6) is apparently linear. This might be predicted from Eq. (8) where it is evident that a log-log plot of $(P-P_o)$ would be linear with unit slope. Experimentally obtained values of P should then be linear, since in the region where measurements were made, P is much greater than P_o. However, it is unwise to attach much significance to the linearity because of the insufficient number of points and the errors involved in the measurements. Further, it is not clear to what extent the low angle reflections affect the linearity.

REFERENCES

1. T. H. Maiman, Phys. Rev Letters 4, 564 (1960).

2. R. J. Collins, D. F. Nelson, A. L. Schawlow, W. Bond, C. G. B. Garrett and W. Kaiser, Phys. Rev. Letters 5, 303 (1960).

3. A. Javan, W. R. Bennett, Jr. and D. R. Herriott, Phys. Rev. Letters 6, 166 (1961).

4. A. D. White and J. D. Rigden, Proc. Inst. Radio Engrs. 50, 7 (1962).

5. A. L. Bloom, Appl. Phys. Letters 2, 101 (1963).

6. E. I. Gordon, A. D. White and J. D. Rigden, Proceedings of the Symposium on Optical Masers 13, 303 (1963).

7. J. D. Rigden and A. D. White, Quantum Electrodynamics, Paris (1963).

8. A. D. White and J. D. Rigden, Appl. Phys. Letters 2, 211 (1963).

9. G. K. Moeller and T. K. McCubbin, Jr., Appl. Optics 4, 1413 (1965).

10. A. L. Bloom, W. E. Bell and R. C. Rempel, Appl. Optics 2, 317 (1963).

11. A. G. Fox and Tingye Li, Bell Syst. Tech. J. 40, 453 (1961).

12. G. D. Boyd and J. P. Gordon, Bell Syst. Tech. J. 25, 499 (1961).

13. G. D. Boyd and H. Kogelnik, Bell Syst. Tech. J. 41, 1347 (1962).

14. E. I. Gordon and A. D. White, Appl. Phys. Letters 3, 199 (1963).

15. W. V. Smith and P. Sorokin The Laser, McGraw-Hill, 1966.

16. G. Birnbaum, Optical Masers, Academic Press, 1964.

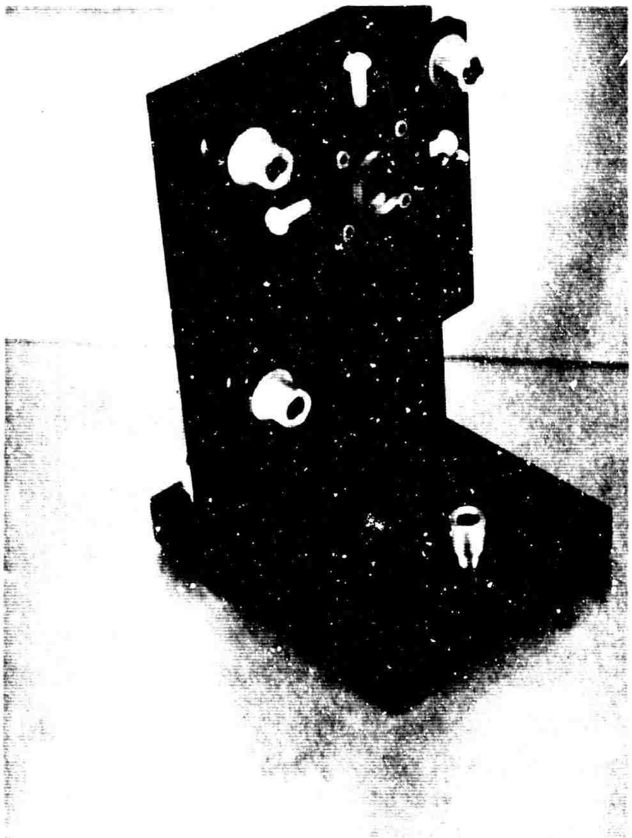

Figure 1 Mirror mou

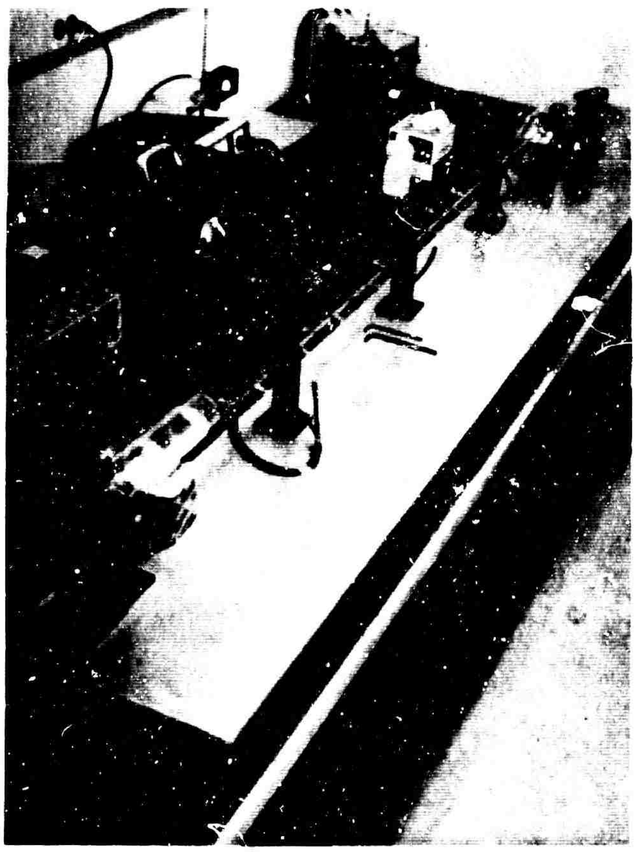

Figure 2 Laser tube

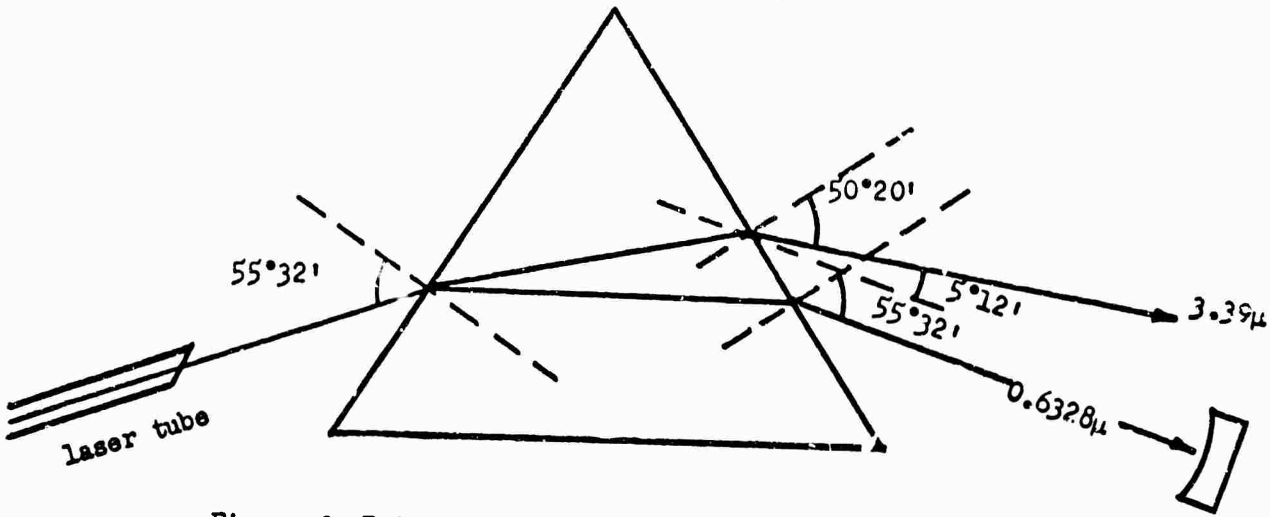

Figure 3 Prism arrangement

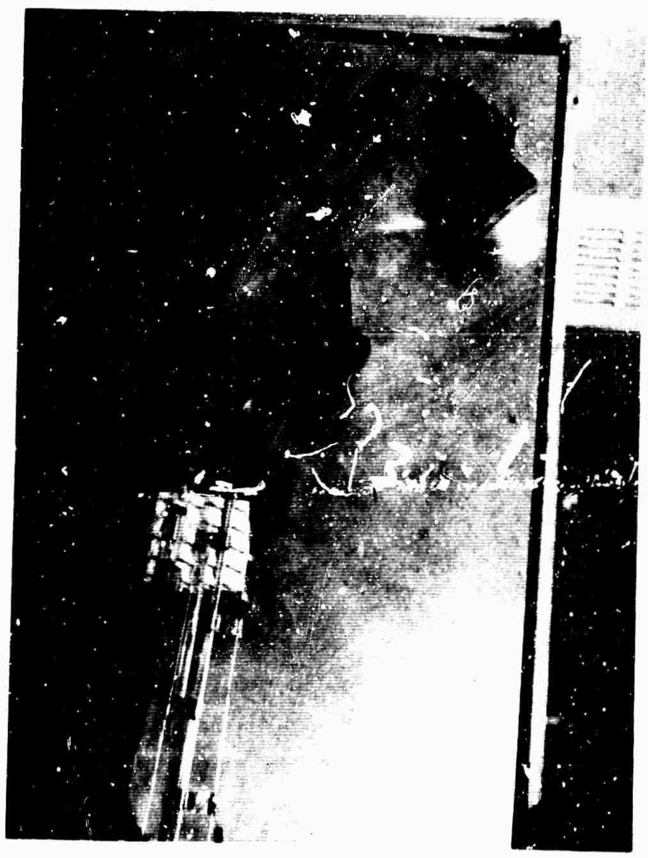

Figure 4 Laser tube showing prism section

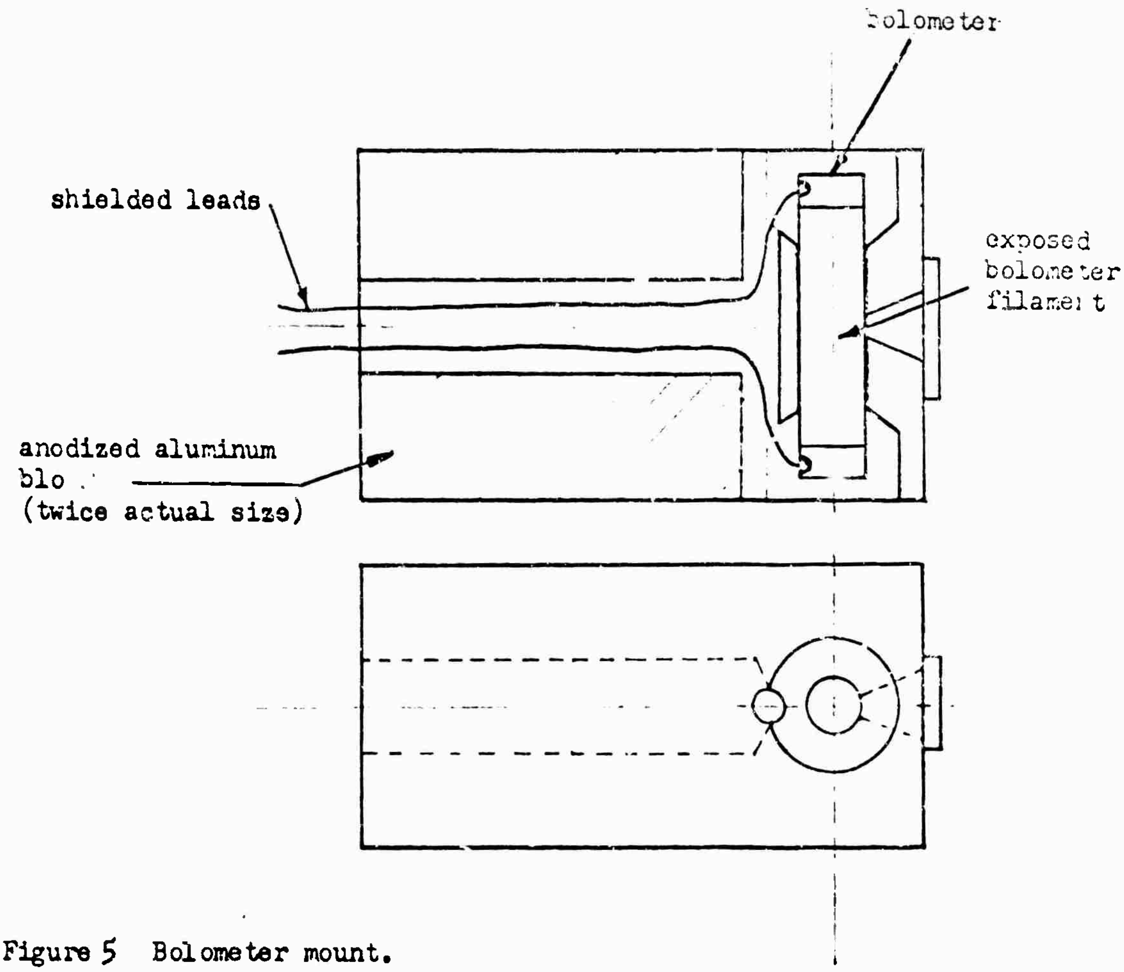

Figure 5 Bolometer mount.

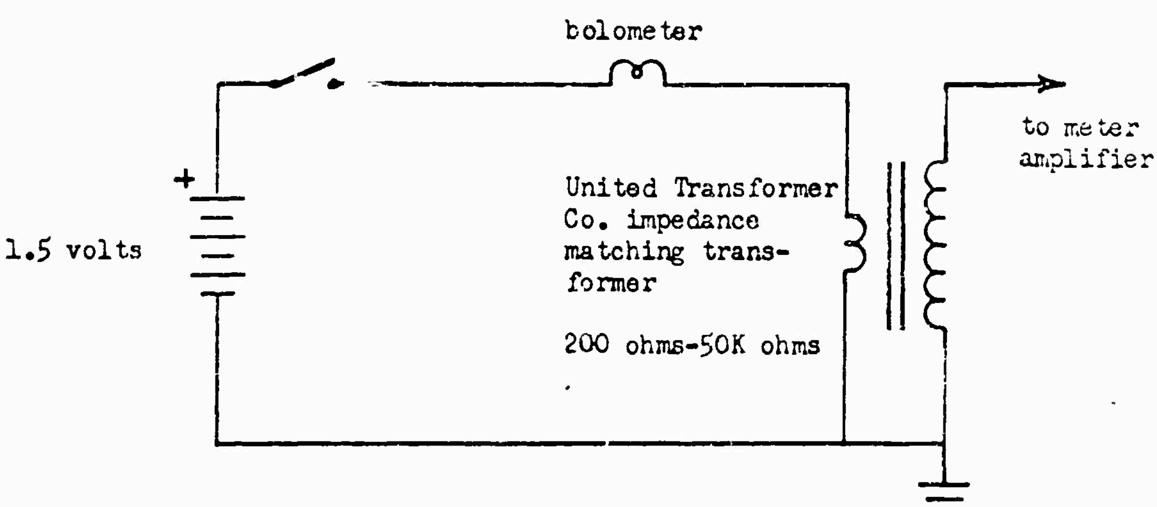

Figure 6 Bolometer circuit

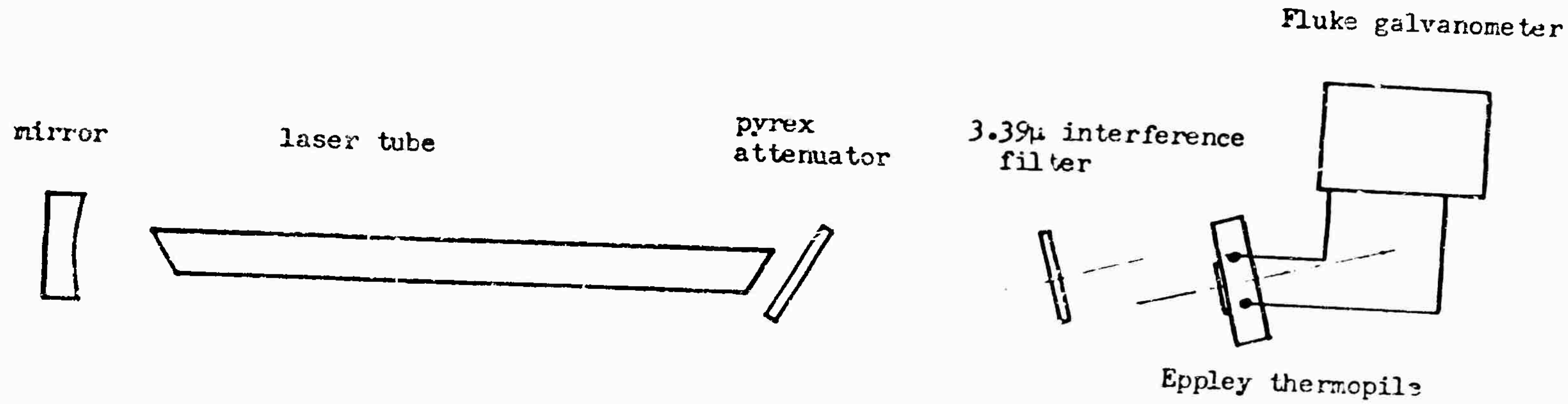

Figure 7 Experimental setup for measuring superradiance

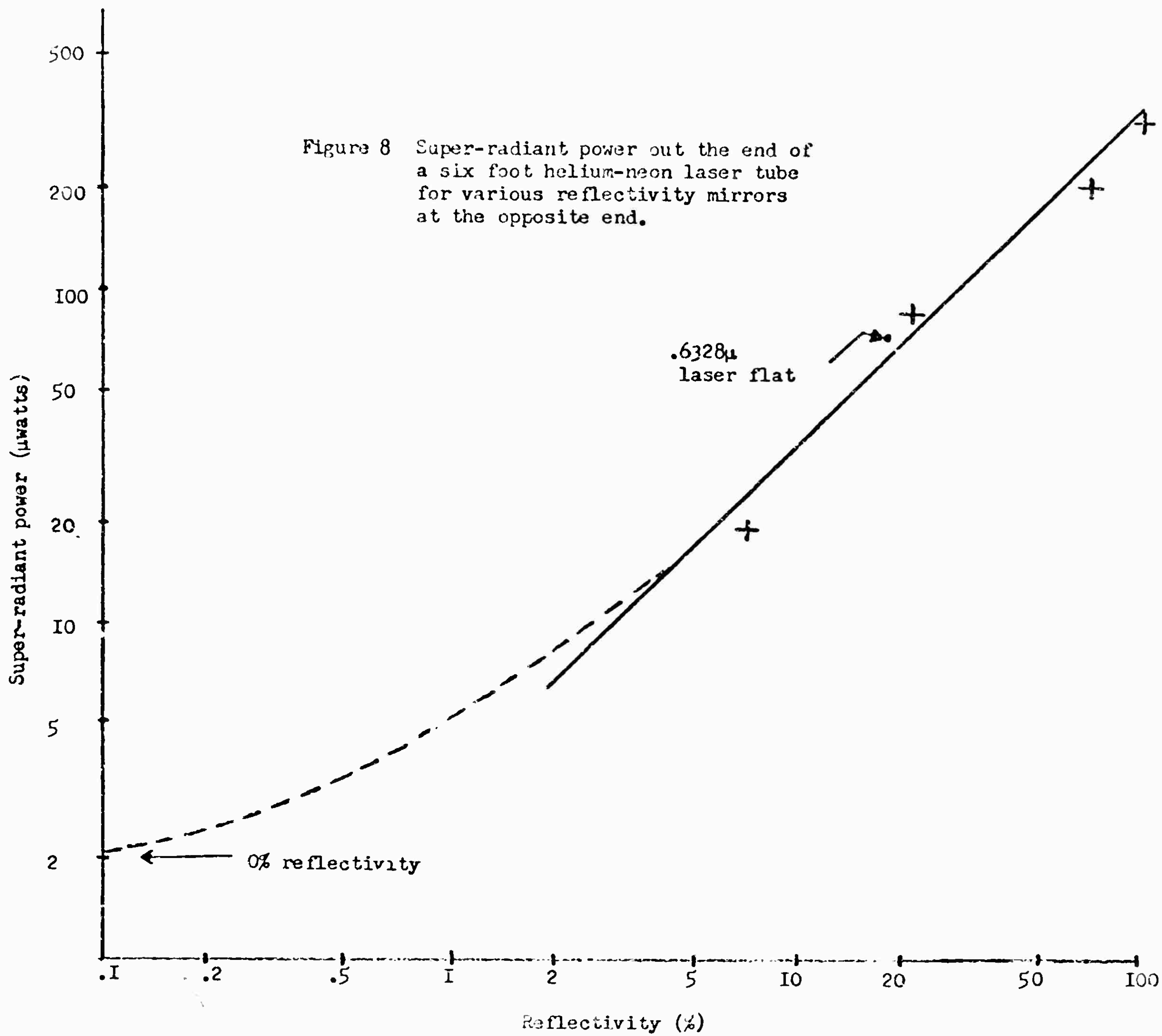

Figure 8 Super-radiant power out the end of a six foot helium-neon laser tube for various reflectivity mirrors at the opposite end.

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The effect of competition in a 0.6328 micron helium-neon laser from the high-gain 3.39 micron line has been studied. The 50 milliwatt laser used for the investigation employs a six-foot Brewster-angle tube and has a prism at one end to insure that oscillation occurs only at 0.6328 microns. Measurements were made of the 3.39 micron superradiance from one end of the tube when various calibrated reflectors were placed at the other end. With a typical dielectric coated mirror, designed for maximum reflectivity at 0.6328 microns, the superradiant 3.39 micron power from the other end of the tube was 75 microwatts. This result shows that in a 6 foot visible laser filled with a 10:1, He^3-Ne mixture and employing a single prism for frequency selection, the 3.39 micron superradiance does not significantly affect the visible output power. However, the superradiance is about 2 orders of magnitude larger than estimated from theory, and presumably results mainly from multiple reflections from the tube walls.

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